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A STUDY OF SMOKE MOVEMENT IN AN AIRCRAFT FUSELAGE.(U)
JAN 78 T J METHVEN, J S WEBSTER
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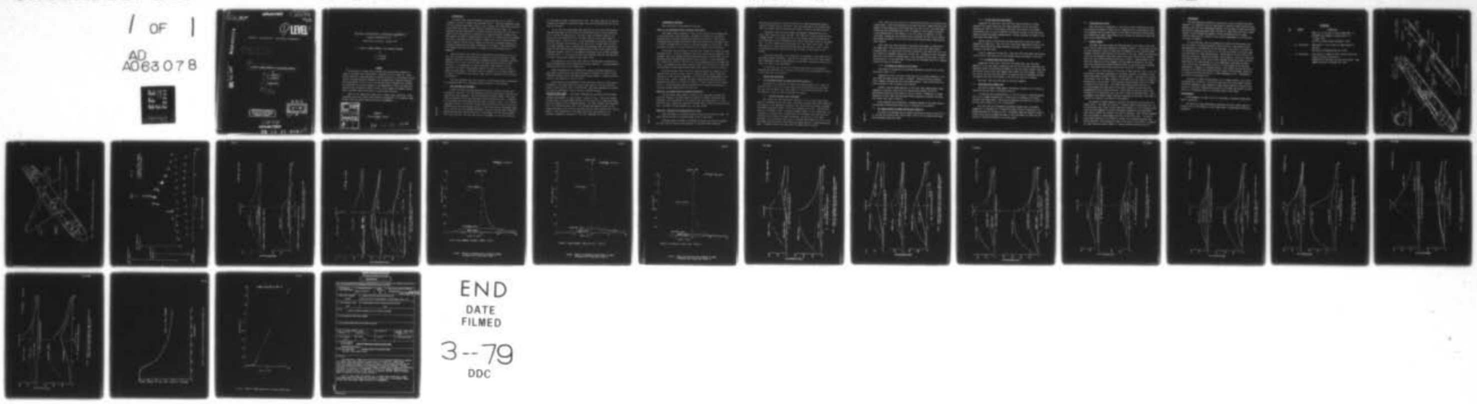

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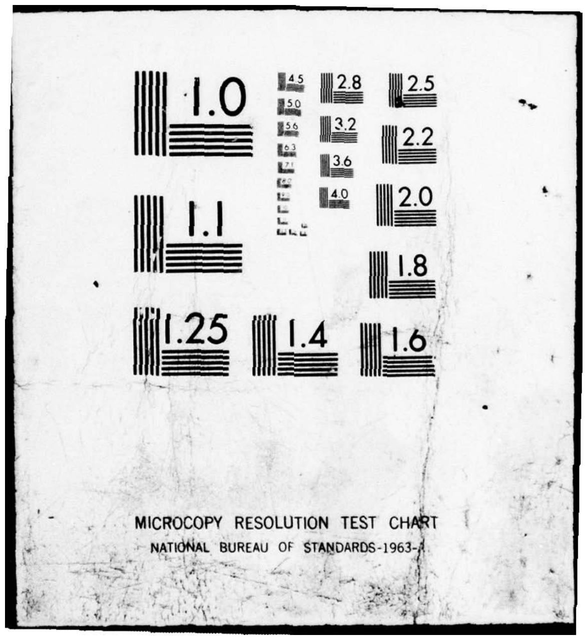
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# A STUDY OF SMOKE MOVEMENT IN AN AIRCRAFT FUSELAGE

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## SUMMARY

The migration of smoke from in-flight fires and possible measures to improve its removal have been studied in ground tests on a Comet 4B. Under normal conditions, smoke generated in various sections in the fuselage followed the air flow and dispersed throughout the fuselage before passing overboard. Biasing discharge to the front or rear affected smoke clearance only slightly but directing the total air supply to the compartment in which the smoke was generated had a beneficial effect locally, at the expense of adjacent cabins. Better clearance might be obtained in a more modern aircraft.

Tests in the flight deck showed that, in smoke laden conditions, flight instruments were best viewed with individual illumination in low ambient light. Further work with higher smoke densities is recommended.

## 1 INTRODUCTION

In recent years several passenger aircraft have been put at risk or crashed as a result of smoke from in-flight fires[1,2]. Materials Department, RAE have been making a particular study[3] of the in-flight fire hazard from electrical faults which can produce a rapid build up of smoke and toxic fumes. An apparatus has been constructed to provide controlled heating in an air flow of a sample of aircraft material, and study of its behaviour before flaming occurs. Measurements are made of temperatures of initiation of endothermic and exothermic reactions; a semi-quantitative estimate is made of the acid or alkaline fumes using a bubbler; and the rate of smoke evolution and its maximum intensity are assessed by measuring the (light) absorbance of the smoke. These experiments have enabled the above properties of a range of aircraft materials to be compared.

The next phase of the study was to extrapolate the laboratory results to full scale conditions using an aircraft cabin and controlled heating of large samples of material. The assistance of Engineering Physics Department, RAE was required to set up this test with cabin air flows representative of flight conditions. In preparation for these experiments smoke movement would be observed in the cabin, using harmless smoke, to decide on the best siting of smoke and fume sensors. Some work required by CAA/AD to study smoke movement and means of dispersal in an aircraft cabin would be combined with the setting up procedure.

This note describes the work carried out by Engineering Physics Department on a grounded Comet 4B to investigate smoke dispersal in the fuselage.

## 2 TEST SPECIMEN AND EQUIPMENT

A Comet 4B, which was time expired and used as a source of spares, was provided for the tests. All the passenger seats had been removed, together with carpets and other equipment. The air distribution system, however, was intact, with the exception of the rear discharge valve and extraction fans. A diagram of the system, with the distribution flow path, is shown in Fig 1. Air from the wing ducts is fed to the central silencer box, and thence up risers to port and starboard roof ducts running fore and aft to the front and rear passenger cabins. The air leaves the ducts through rectangular outlets located between frames and passes down the walls behind the trim to be discharged into the cabin through floor level grilles. The roof duct slots are arranged to recirculate cabin air

by entrainment through a perforated roof trim. The flight deck air is supplied through 'foot warmers'; windscreen demist air can also be selected, but was not used in the tests.

Air in the rear cabin passes down the cabin to the toilets and pressure dome and then under the floor where it reverses direction to flow forward and out of the rear discharge valve. The front cabin air passes forward to the galley area, goes under the floor, and then flows aft to the front dump or discharge valve. Flight deck air is also discharged to the galley with assistance from equipment cooling fans, and the galley air is drawn under the floor by further equipment fans. Normally the rear discharge valve is controlled in flight by cabin pressurisation requirements and air flow to the forward cabin regulated by manual control of the dump valve adjacent to the forward (standby) discharge valve. In the tests with the rear discharge valve and the dump valve in use the valves were arranged to give equal flows.

Air supplies up to the full cabin flow of 0.68 kg/s were obtained from a ground pressurisation truck connected to the port wing duct. Flow was measured using an orifice plate in the supply duct.

Smoke was generated at a standard rate using a Lede Smoke Generator in which smoke is produced by heating a fine spray of cosmetic oil which is then dispersed through a nozzle by carbon dioxide under pressure. Three alternative positions were employed as shown in Fig 2.

Smoke densities were assessed at three positions (Fig 2) by measuring the absorbence of the smoke laden air using a light source on the floor directed towards a photo-electric cell on the ceiling. The three readings were recorded on a chart as absorbance (optical density), defined as $\log_{10} \frac{\text{Intensity without smoke}}{\text{Intensity with smoke}}$. The sensor readings were recorded on one instrument through a multiplexer; a typical output is shown in Fig 3. Where the reading fluctuated due to varying smoke density, as for sensor No.3, a smoothed average curve was plotted in the subsequent figures. The chart recorder was calibrated with a 0.8 absorbance gauze, with 1.95 m between the lamp and sensor in the flight deck (No.1), and 1.55 m in the front and rear cabin sensors (Nos.2 and 3), (Fig 3). The calibration for the flight deck sensor was adjusted to an equivalent lamp/sensor distance of 1.55 m for compatibility of results.

## 3 EXPERIMENTAL PROCEDURE

The tests were in three phases as follows:

### Phase I: Air discharge effects on smoke distribution

With smoke sources located, in turn, in the rear and front fuselage and in the flight deck, tests were made to determine the effect of alternative discharge valve settings on smoke distribution and dispersal. The air was discharged equally between the forward dump valve and the rear discharge valve; or entirely through the rear valve; or entirely through the front valve. Tests were made at the full air flow (0.68 kg/s) and a reduced rate (0.34 kg/s).

Preliminary tests were made to equalise flow through the forward and rear discharge valves. With the fuselage access doors closed and air supplied to the fuselage, flows were checked by fixing large polythene collector tubes over the discharge points and measuring the mean outlet velocity. It was necessary to fit a restrictor orifice of 102 mm in the rear discharge position to equate the flows. An attempt was then made to measure cabin air velocities, but these were only detectable at the supply grilles where they ranged from 0.05 to 0.20 m/s.

With the aircraft doors closed the required airflow was supplied to the fuselage from the ground truck. After zeroing the smoke sensors, smoke was switched on in the selected compartment, the starting time being marked on the recorder chart. After 10 minutes the smoke supply was switched off and the absorbance recorded for a further 10 minutes. A typical chart record is shown in Fig 3. The access doors were then opened with air supplies maintained to clear any residual smoke before the next test.

### Phase II: Air supply effects on smoke distribution

For the various smoke source locations, tests were made to assess the effect of zoning of the conditioning air supplies on smoke distribution and dispersal. Air was supplied to the forward cabin and flight deck, or to the rear cabin only. Tests were made with 0.68 kg/s and 0.34 kg/s airflow, with the discharge equally divided between front and rear valves.

### Phase III: Visibility and smoke generation tests

Tests were made to correlate absorbance values with visibility range. No cabin airflow was used, to provide denser and more even smoke.

Initially tests were made to determine the distance at which a standard eye chart could be read by three subjects in different smoke densities.

The chart was brightly lit from the front by two lamps shining from approximately 45° either side of the chart. The tests were made in the forward chain with the doorways sealed, using the No.2 sensor to measure the smoke density.

Additional tests were made using an internally illuminated box with a plain 'opal' glass face (250 × 300 mm). The 150W bulb could be controlled with a dimmer switch. At an absorbence of 1.2 the visible range was determined for two illumination levels, determined with a Weston Light Meter close to the glass face: 85 cd/m$^2$ (representing an aircraft exit sign level) and 4 cd/m$^2$. The smoke density in these tests was measured along the observers' line of vision by mounting the sensor beside the box and the lamp 1.55 m in front of the sensor.

Tests were also made in the flight deck to determine at what smoke density instruments became unreadable. Some of the instruments were unlit while others were illuminated either by edge lighting or individual lights with reflectors to direct the light at the instruments.

In the final test the output of the smoke generator was determined by measuring the absorbance as a function of time with the smoke generator running in the cabin with no air supply.

## 4 RESULTS AND DISCUSSION

### 4.1 Air discharge effects on smoke distribution (Phase 1)

The build up of smoke and its decay after smoke generation is stopped are plotted in Figs 4 to 6 for various smoke sources and discharge valve settings, with the full air mass flows; and in Figs 7 to 9 with halved mass flows. Air was supplied to rear and front cabins and the cockpit.

#### 4.1.1 At full air mass flow (0.68 kg/s)

Fig 4 shows the time variation of absorbance for the three sensors when smoke is introduced in the rear cabin. With both discharge valves open (Fig 4(a), the majority of the smoke was carried aft with the prevailing airflow, although some smoke penetrated forward to the front fuselage and cockpit. Equilibrium density was reached in about 5 minutes, somewhat longer for the flight deck, and clearance in a similar time. Closing the front discharge valve (Fig 4(b)) had relatively little effect, as might be expected: the majority of the smoke continued to be carried aft over sensor 3, although the aftward flow of air from the flight deck and forward cabin halved the small quantity of smoke penetrating there. Clearance time in the rear cabin was significantly quicker.

Fig 5 shows the time variation of absorbance when smoke is introduced into forward cabin. With both discharge valves open (Fig 5(a)), smoke intensity rose rapidly in the forward cabin and flight deck, but not at all in the rear cabin. Closing the front discharge valve drove the smoke aft and reduced the density in the forward areas at the expense of the rear cabin, as expected. On the other hand, closing the rear discharge valve increased the flow of air forward and reduced the density in the front cabin without significantly affecting the other sensors.

Fig 6 shows the time variation of absorbance when smoke is generated in the flight deck. With both discharge valves open (Fig 6(a)) smoke density increases there to a high level over about 10 minutes, with some build up in the front cabin but negligible penetration further aft. Closing the front discharge valve has little effect, although smoke is now reaching the rear cabin in small concentrations. On the other hand closing the rear discharge (Fig 6(c)) slightly reduces the density everywhere.

#### 4.1.2 At reduced air mass flow (0.34 kg/s)

The results of repeating the preceding experiments with half the airflow are given in Figs 7 to 9.

Comparison of Fig 7 with Fig 4 shows that with the smoke generator in the rear cabin the smoke density there is doubled. Closing the front discharge valve somewhat increases the rear cabin smoke density. Equilibrium values are barely achieved in the 10 minutes test duration.

However, with the smoke generator in the front cabin smoke density there appeared to rise more slowly with the reduced airflow (Fig 8 *cf* Fig 5). Equilibrium values were not reached in the test period. Similarly, for smoke generation in the flight deck the smoke density apparently reduced on halving the airflow rate (Fig 9 *cf* Fig 6).

These anomalies are attributed to inadequate mixing of the smoke and air, leaving smoke concentrations which were not detected at the sensors.

### 4.2 Air supply effects on smoke distribution (Phase 2)

The results of altering the air supply conditions are given in Figs 10 to 12, for the full airflow rate, and in Figs 13 and 14 for the halved flow rate. Both discharge valves were open.

4.2.1 At full mass flow (0.68 kg/s)

Comparison of Figs 4(a), 10(a) and 10(b) shows the effect of three different air supply conditions, for smoke generation in the rear cabin. Supplying all the air to the forward cabin had little effect on the smoke distribution, but, as can be predicted, putting all the air to the rear cabin markedly reduced the smoke reaching sensor 3 whilst carrying it forward to the front cabin and flight deck.

Similar results occurred with the smoke generator in the front cabin. Comparison of Figs 5(a), 11(a) and 11(b), shows that supplying air only to the forward cabin reduced the smoke reaching that sensor - since it is carried through to the rear cabin.

Finally, comparison of Figs 6(a), 12(a) and 12(b) shows again that supplying air only to the front part of the fuselage drives the smoke to the rear.

4.2.2 At reduced mass flow (0.34 kg/s)

Comparison of Figs 7(a), 13(a) and 13(b) shows that, with the smoke generator in the rear cabin, putting all the air into the front cabin gives the anomalous result of increasing the density in the rear cabin, whereas logic (and the results at full flow rate) suggest there should be little change. Putting all the air into the rear cabin gives the expected result of markedly reducing the smoke at the rear cabin sensor, as the air flow carries it forward.

Figs 8(a), 14(a) and 14(b) may be similarly compared.

4.3 Visibility tests (Phase III)

The curve of vision range against absorbance, obtained in the visibility tests with the eye chart, is plotted in Fig 15.

In tests with the illuminated box, it could be seen at a distance greater than 4 m in a smoke absorbance of 1.2 when set at a luminance of 85 cd/m$^2$ (aircraft exit sign level). When the box luminance was reduced to 4 cd/m$^2$ it was then just visible at 3 m in 1.2 absorbance.

The tests with the illuminated instruments showed them to be easily readable at 1 m distance in 1.2 absorbance smoke; without illumination, the reading distance was reduced to 0.5 m. Extraneous light was generally found to hinder vision when an attempt was made to read instruments or signs, but was useful for obtaining bearings in the dense smoke.

4.4 Smoke generator output

This test gave the absorbance v. time curve in Fig 16 which can be used for checking the generator output and for comparison with other smoke sources. It is apparent that the smoke density in the cabin containing the source would have reached much higher levels during the 10 minute test periods if there had been no air conditioning flows.

4.5 General comment

The smoke tests have shown that smoke movement in the cabin is very slow due to low air velocities necessary for passenger comfort. In the Comet, at full air flow conditions, there is sufficient air movement to give a positive smoke dispersal pattern, which follows the direction of air flow. Smoke stratification occurs in the passenger cabins with clearer areas near the floor and ceiling, where the inlet and recirculation ducts have an effect. Smoke movement at the half flow condition was very sluggish with the smoke collecting at the floor under the injection point before drifting slowly to the nearest open discharge valve. This smoke pattern was therefore more difficult to determine.

An increase in the cabin air velocities by directing full flow to only one cabin made a noticeable improvement in the smoke clearance, with smoke carried rapidly away before having a chance to diffuse locally. The Comet air distribution system is bad for smoke clearance as the smoke can only leave the cabins at extreme ends of the aircraft. Thus clearing one area usually results in smoke in other parts of the cabin. The flight deck seems particularly prone to collecting smoke from other parts of the cabin, although this may have been exaggerated by lack of extraction fans. Later types of aircraft usually have provision for air extraction, near the floor, along the fuselage length. This arrangement could improve smoke clearance techniques, particularly the effect of 'zoning' air supplies, and should be investigated.

The density of smoke reached in the tests was generally low and did not impede vision. In-flight fire reports[1,2] indicate heavier smoke densities. In one particular case, vision in the flight deck reduced to 0.5 m, although vision could have been hampered by lack of instrument illumination and high window light levels because the incident took place in daylight. Eye irritation should have been minimal as smoke goggles were worn by the first pilot. To test at higher smoke densities, for visibility effects and for measuring smoke from burning material, the selenium cell used in the present tests should be replaced by a more sensitive sensor capable of reading absorbance greater than 2.0.

## 5 CONCLUSIONS

The smoke densities obtained in these tests, using a standard Lede Smoke Generator in a Comet 4B, were not high enough to severely impede vision but were adequate, with the aid of absorbance sensors, for the study of smoke distribution. The method of measuring smoke density by means of light absorbance over a fixed distance proved satisfactory, though it would need modification at higher densities which would be required in any further experiments on the visibility of flight instruments.

It was found that, with the discharge air equally divided between front and rear valves, the smoke injected at various points in the pressure cabin moved generally in the direction of the airstream. The effects of biasing the air discharge wholely to the front or to the rear were shown to be fairly small and predictable, at least quantitatively - smoke moved in the direction of the resultant airstream. Similar conclusions were reached as a result of zoning the air supplies wholely to the front or rear fuselage rather than equally divided. Supplying all the conditioning air to the compartment containing the smoke source diluted the concentration locally but at the expense of the adjacent compartments. However, in a modern aircraft, which usually has exit grilles at the base of the cabin walls along the whole length of the fuselage, zoning the air supplies could form the basis of a smoke management drill. Confirmatory tests would be necessary first.

Visibility in smoke has been shown to be a complex problem, even without considering eye irritation. The tests showed that with 'white smoke' indirect instrument lighting or back lighting of signs helped visibility, whilst strong natural or artificial lighting was scattered by the smoke and reduced the eyes ability to distinguish objects in the darker parts of the cabin.

Acknowledgment

Acknowledgments are made to Mr A.J. Christopher of Materials Department, RAE for assistance.

The results of these preliminary experiments provide a useful basis for further study of the movement of toxic fumes which is being made by Materials Department.

## REFERENCES


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| 2 | A.J. Christopher | Some aspects of fire, smoke and fume hazards in aircraft. RAE Technical Memorandum Mat 262 (1976) |
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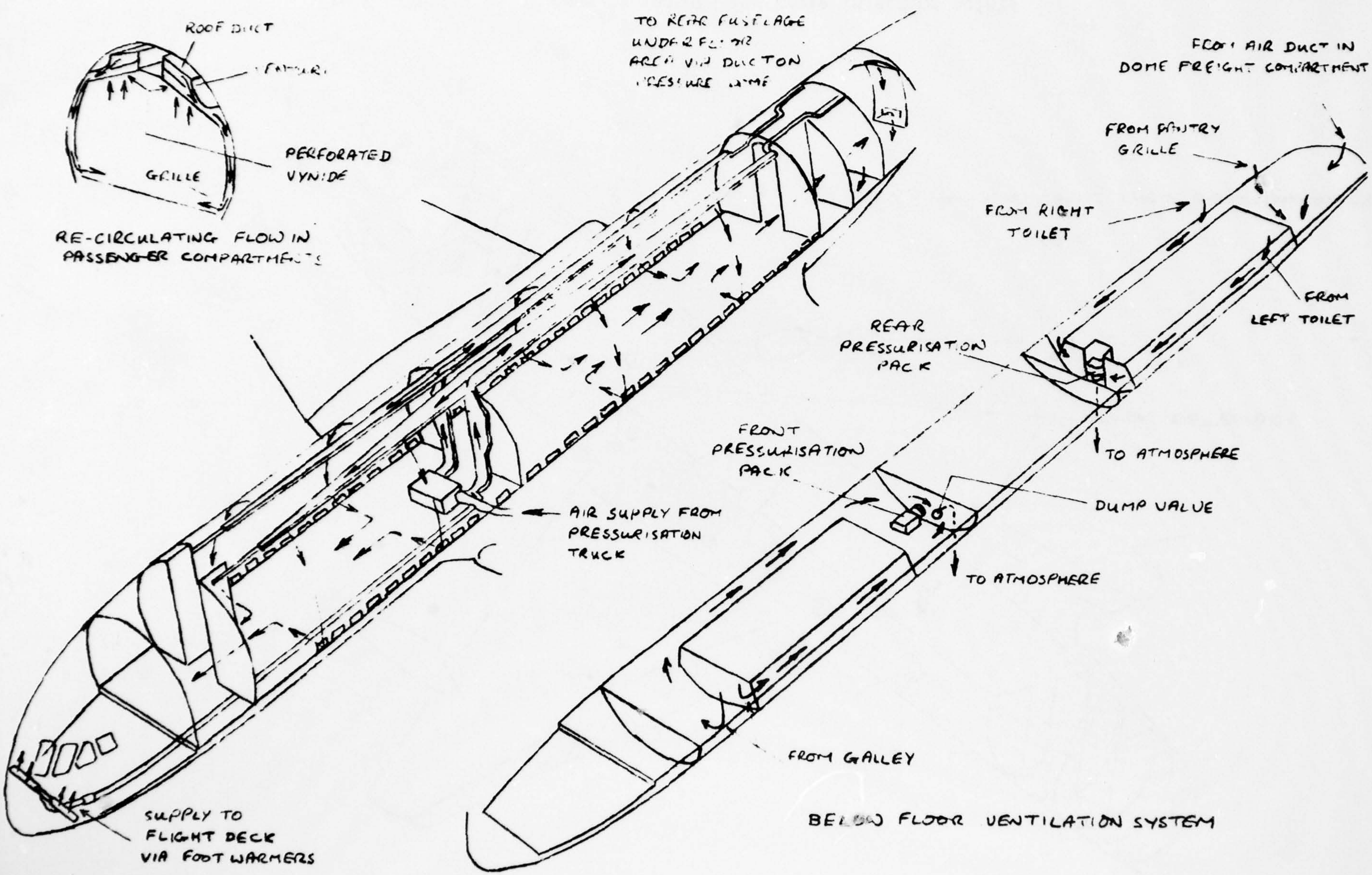



Fig 1 Comet 4B ventilation system

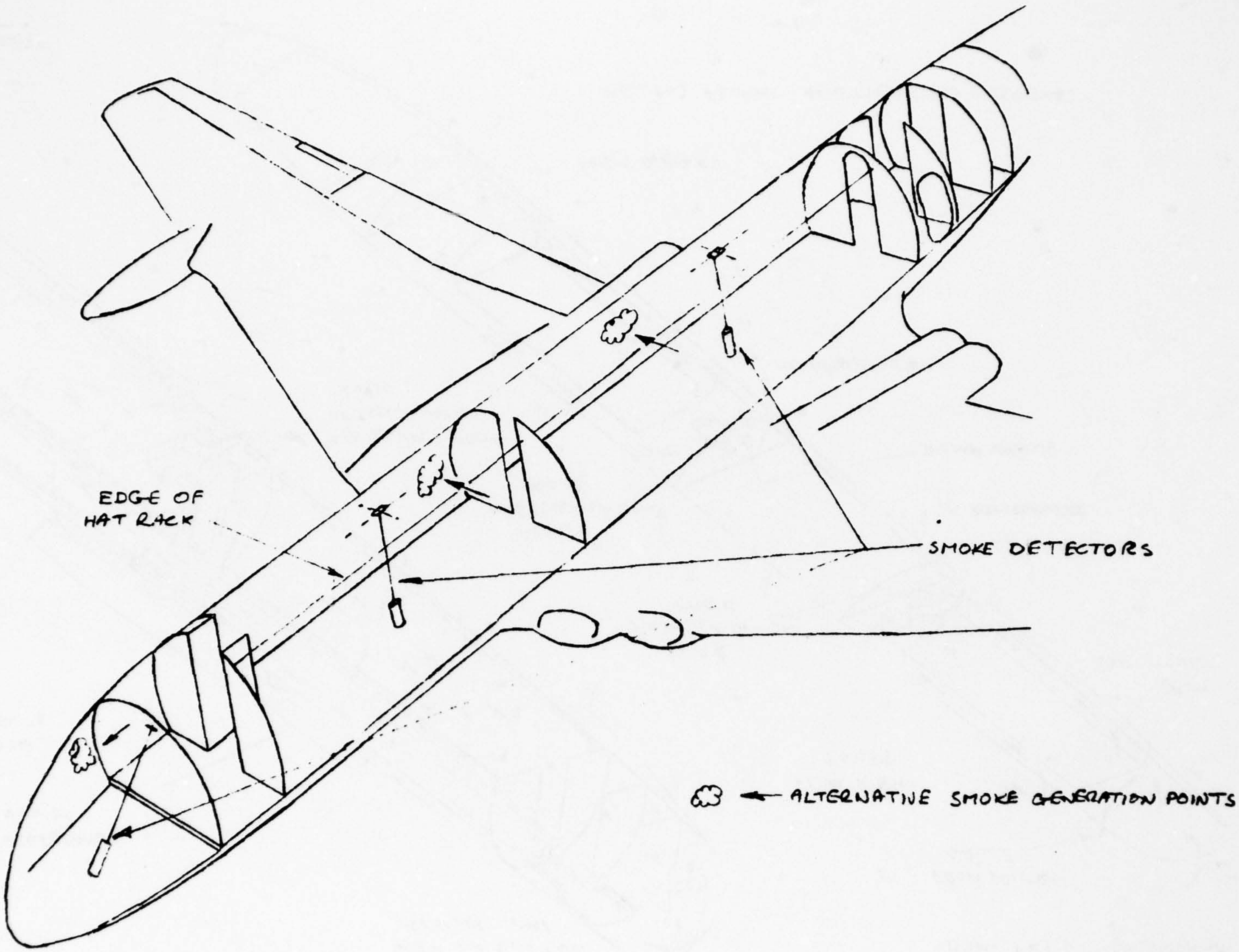



Fig 2 Positions of density sensors and smoke injection points

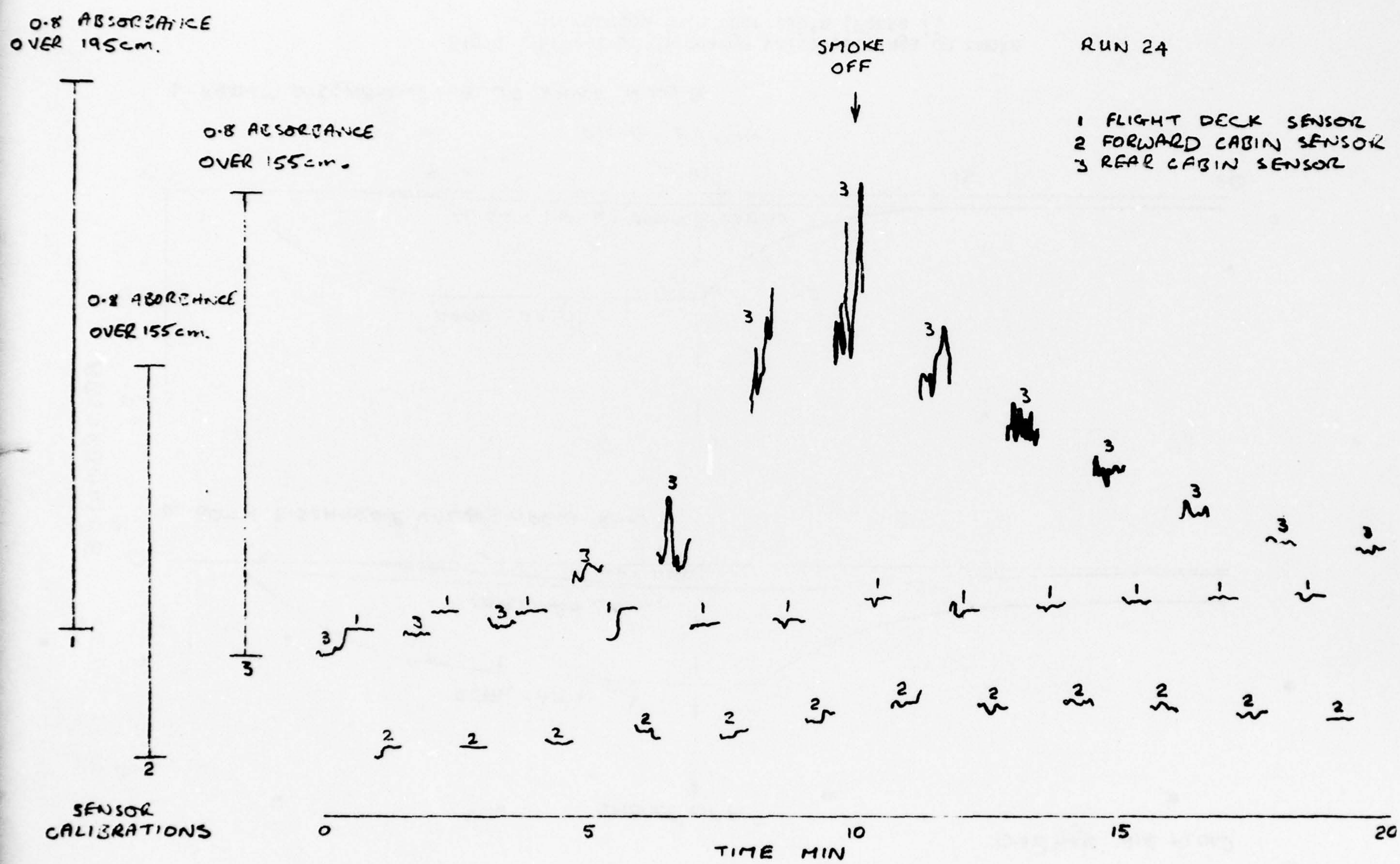



Fig 3 Typical trace from sensors

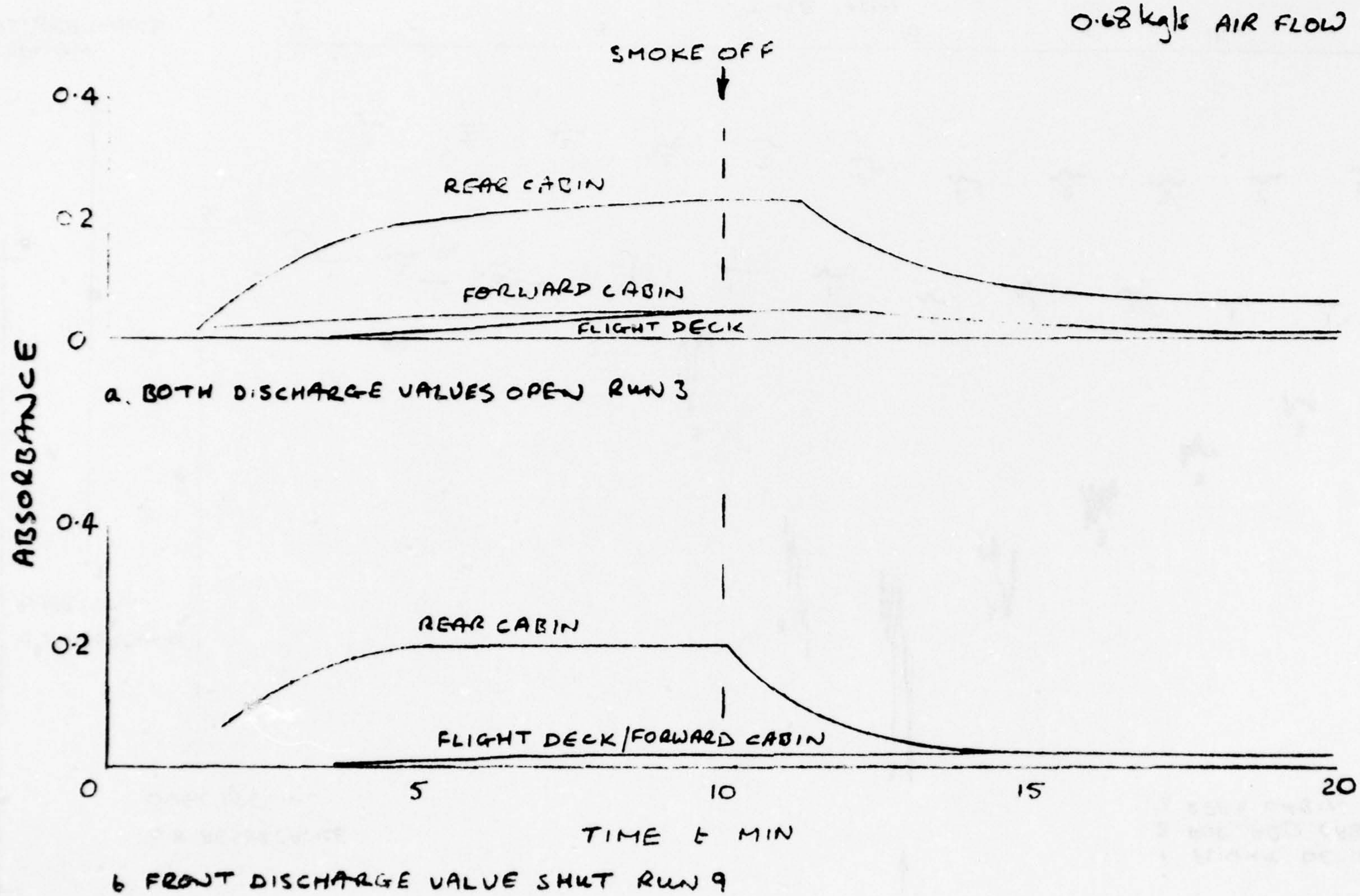



Fig 4 Effect of discharge valve settings on smoke introduced into rear cabin (Phase I)

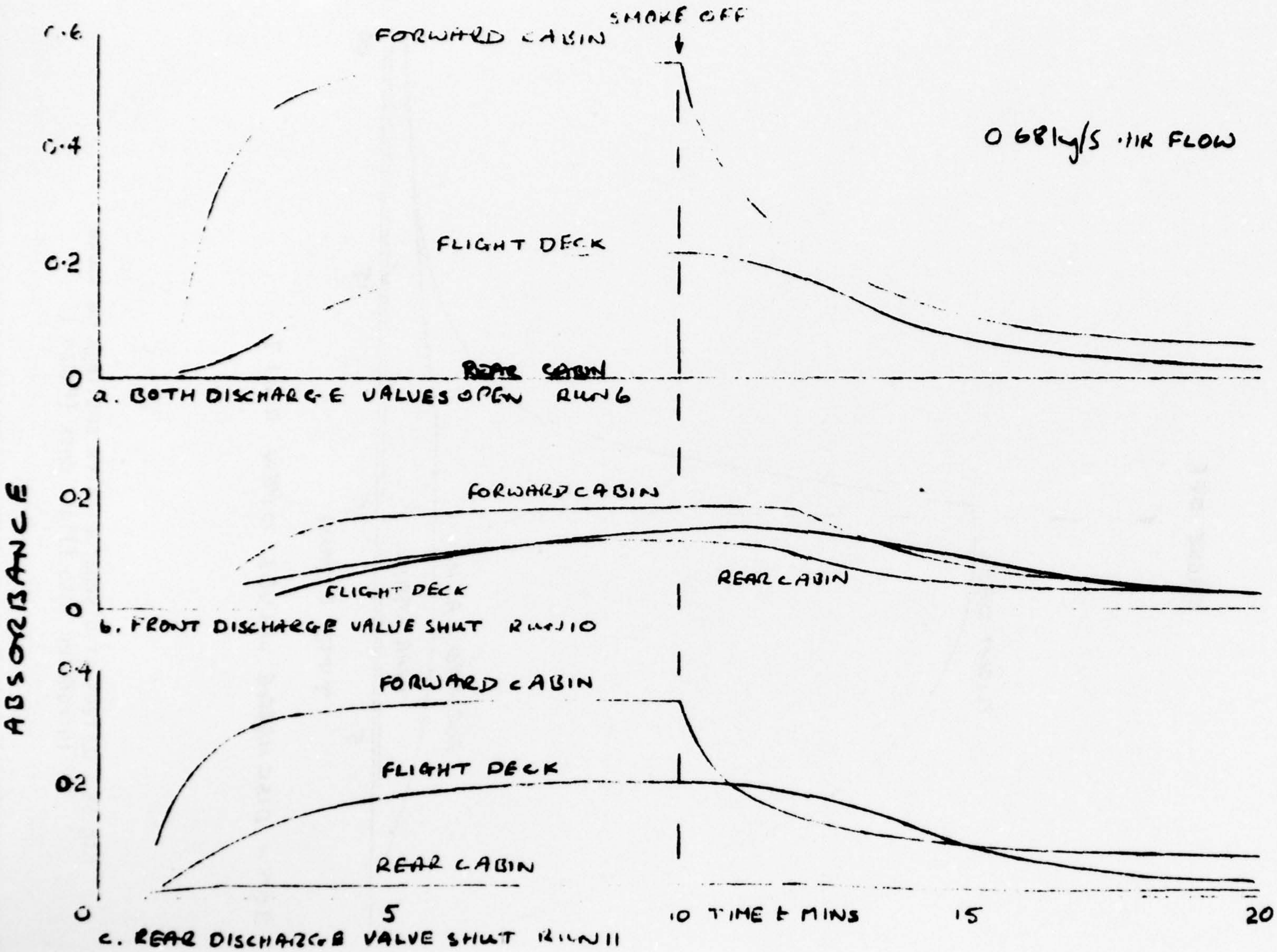



Fig 5 Effect of discharge valve settings on smoke introduced into forward cabin (Phase I)

Fig 6a

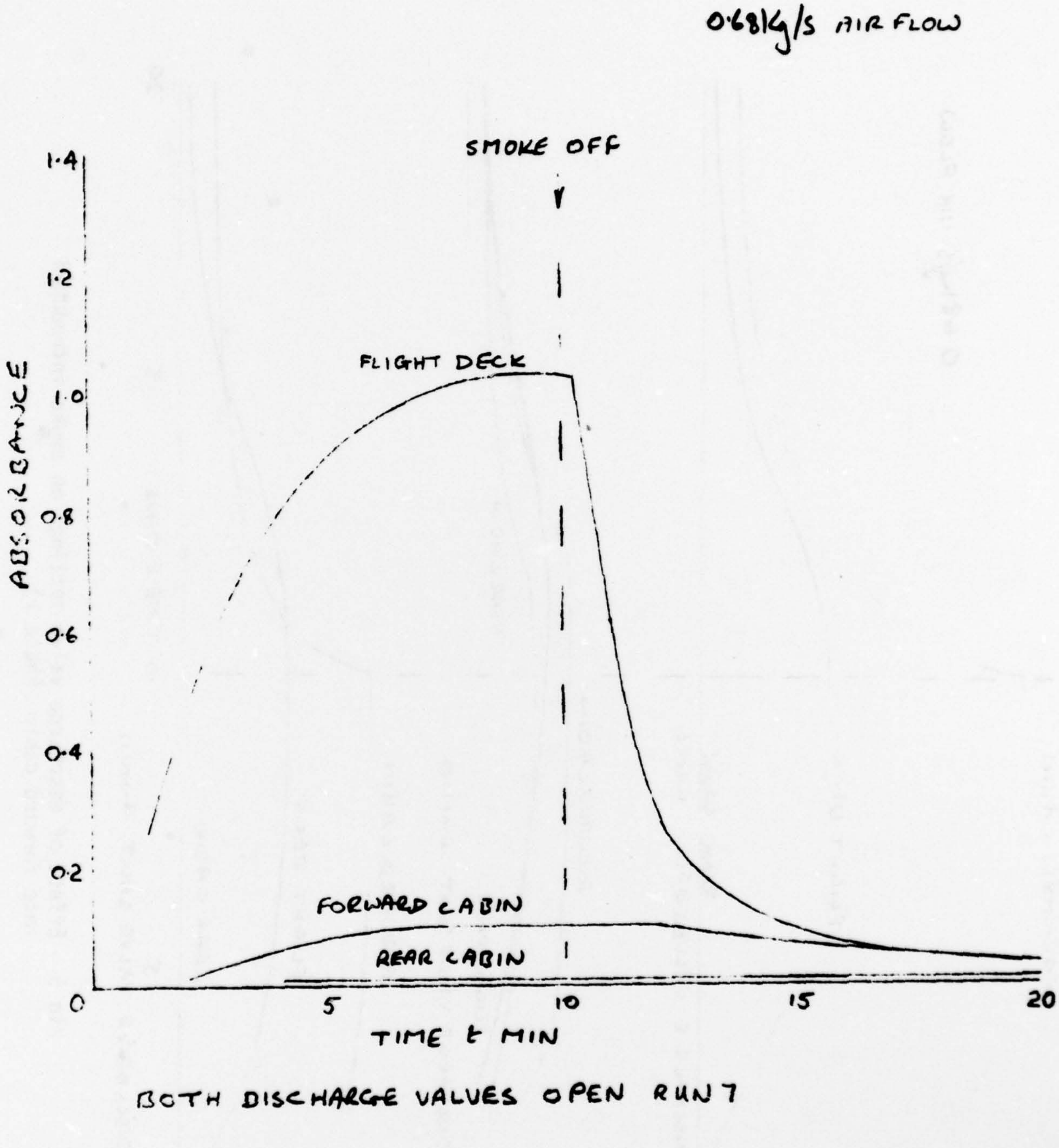



Fig 6a Effect of discharge valve settings on smoke introduced into flight deck (Phase I)

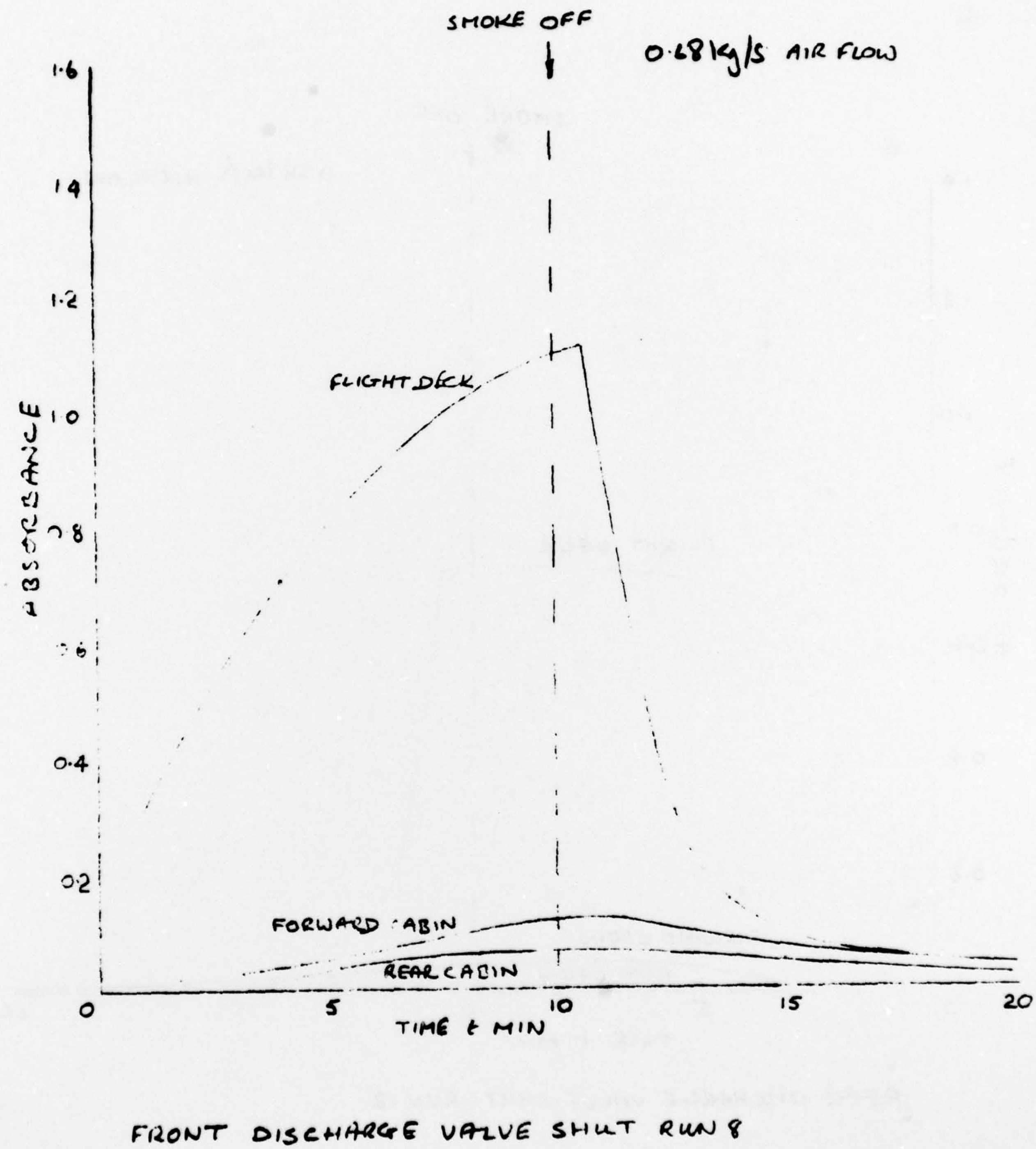



Fig 6b Effect of discharge valve settings on smoke introduced into flight deck (Phase I)

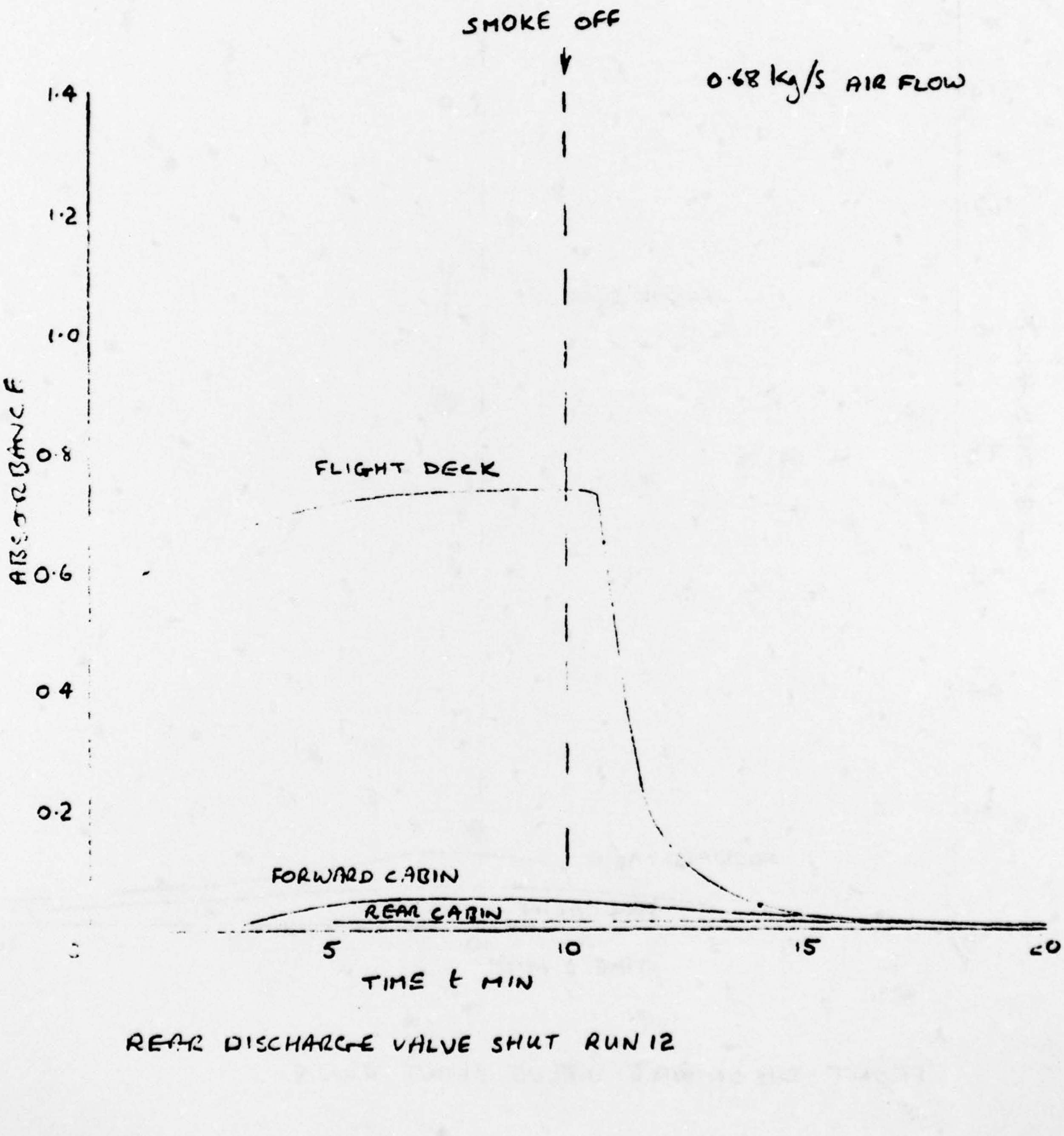
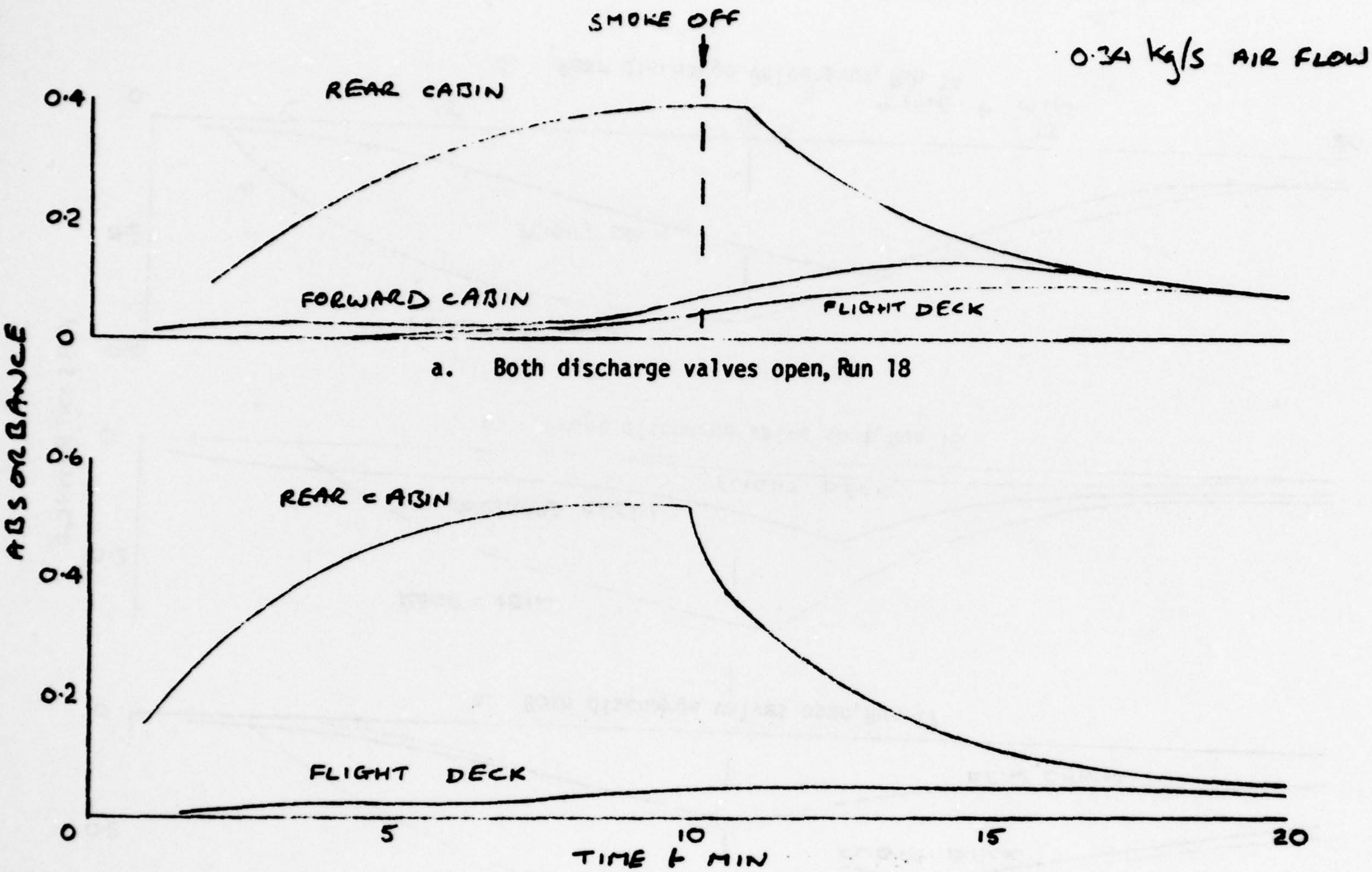


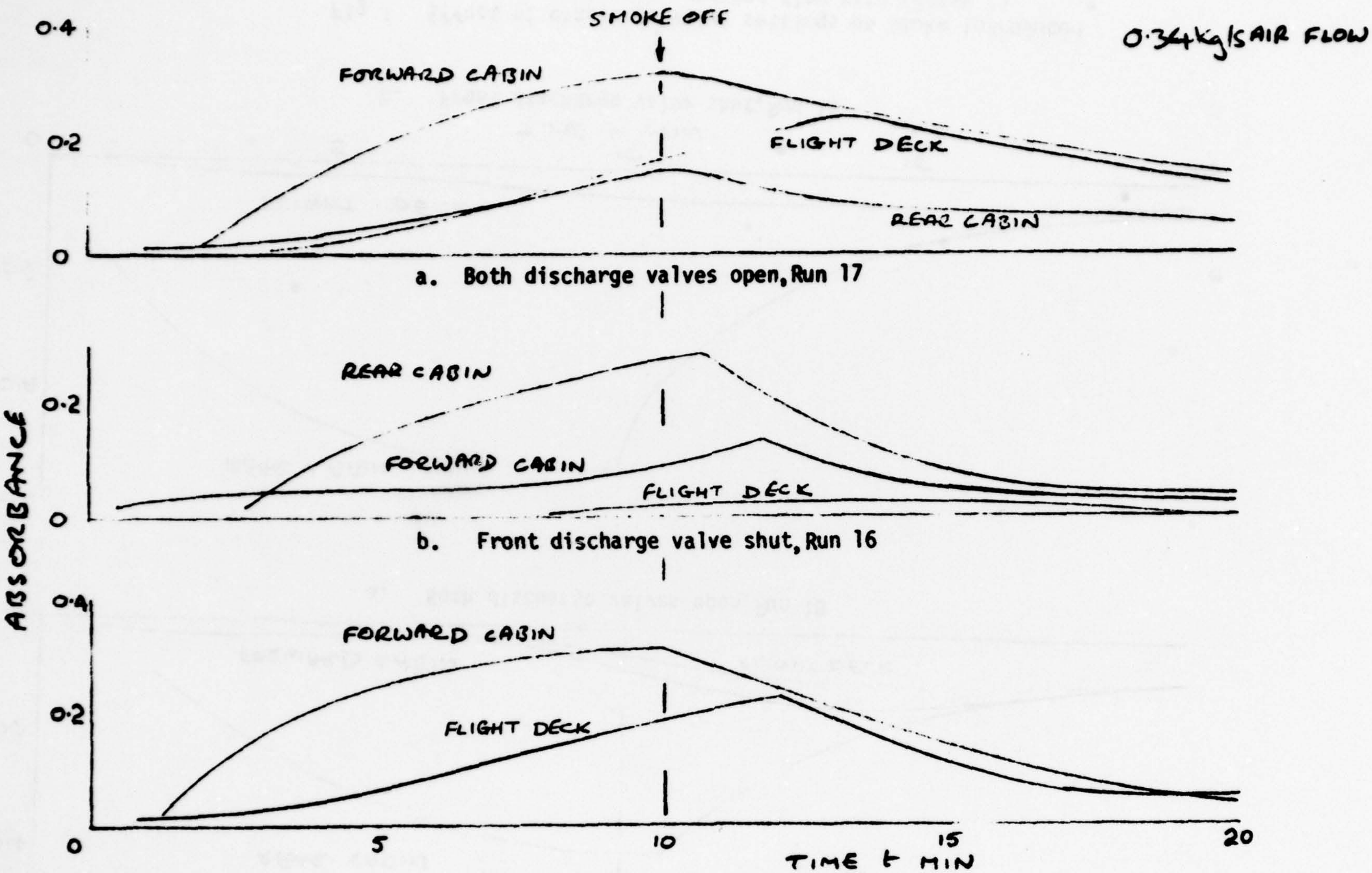

Fig 6c Effect of discharge valve settings on smoke introduced into flight deck (Phase I)




a. Both discharge valves open, Run 18

b. Front discharge valve shut, Run 15

Fig 7 Effect of discharge valve settings on smoke introduced into rear cabin with reduced flow rate (Phase I)

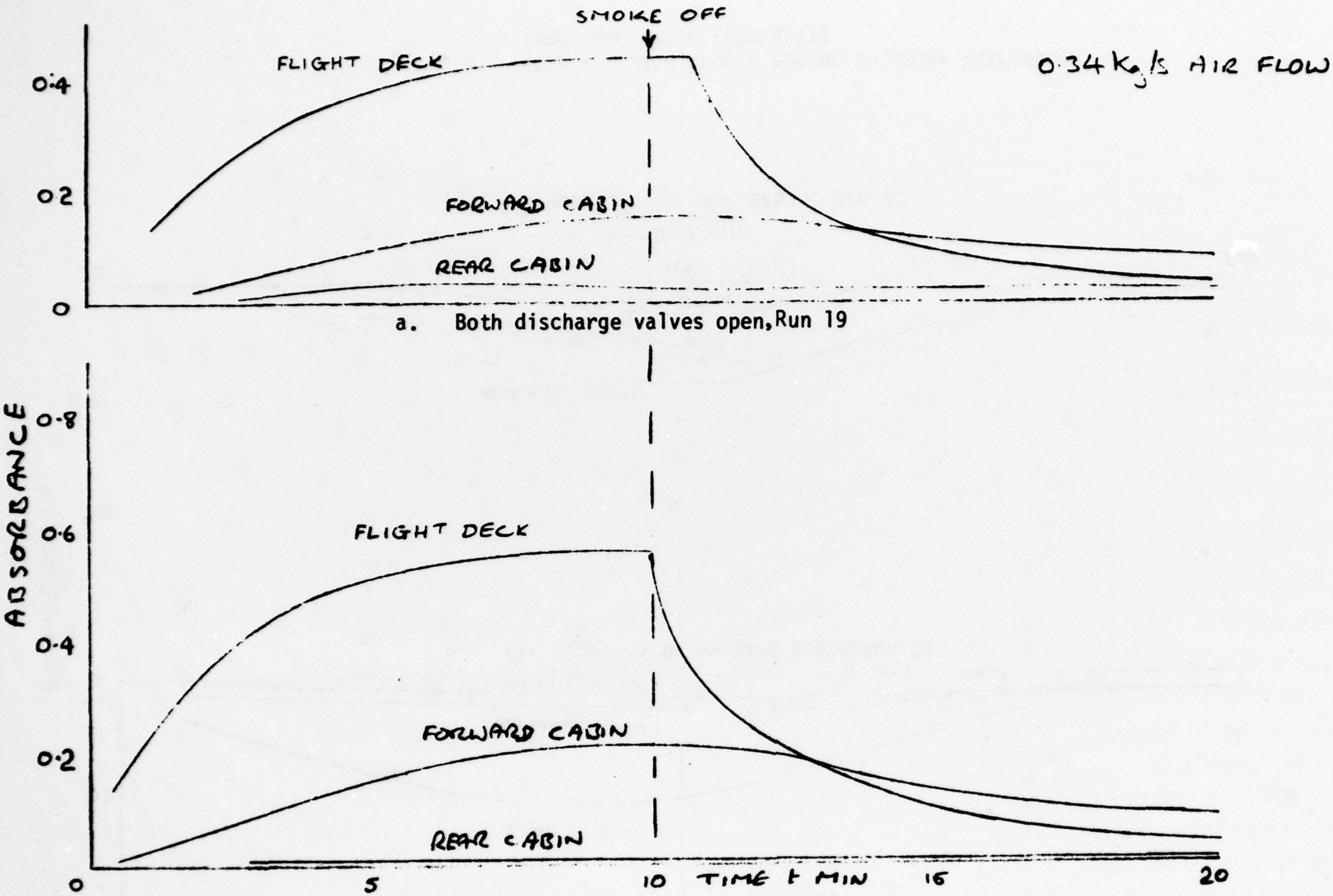



a. Both discharge valves open, Run 17

b. Front discharge valve shut, Run 16

c. Rear discharge valve shut, Run 14

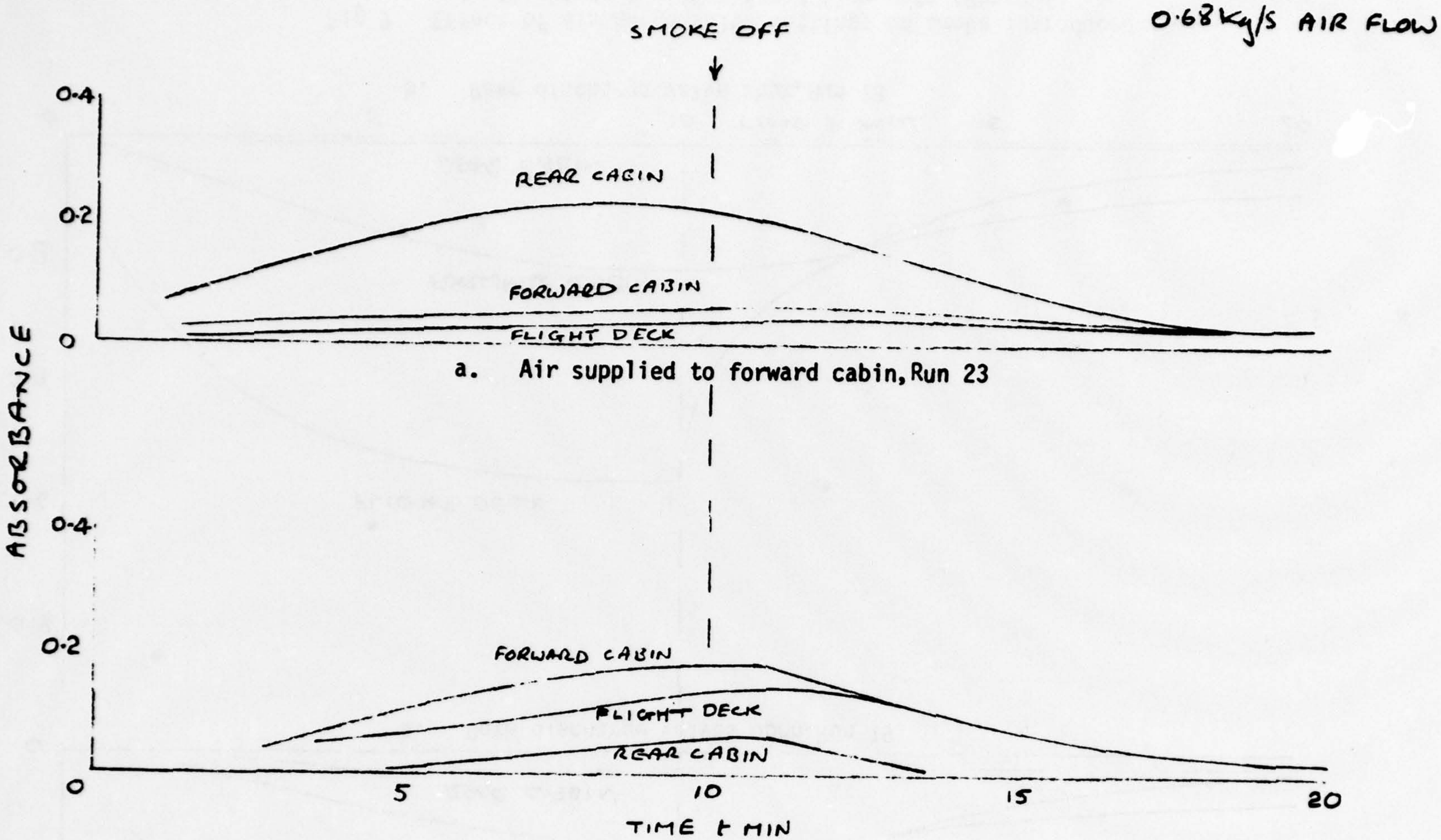
Fig 8 Effect of discharge valve settings on smoke introduced into forward cabin with reduced flow rate (Phase I)




a. Both discharge valves open, Run 19

b. Rear discharge valve shut, Run 13

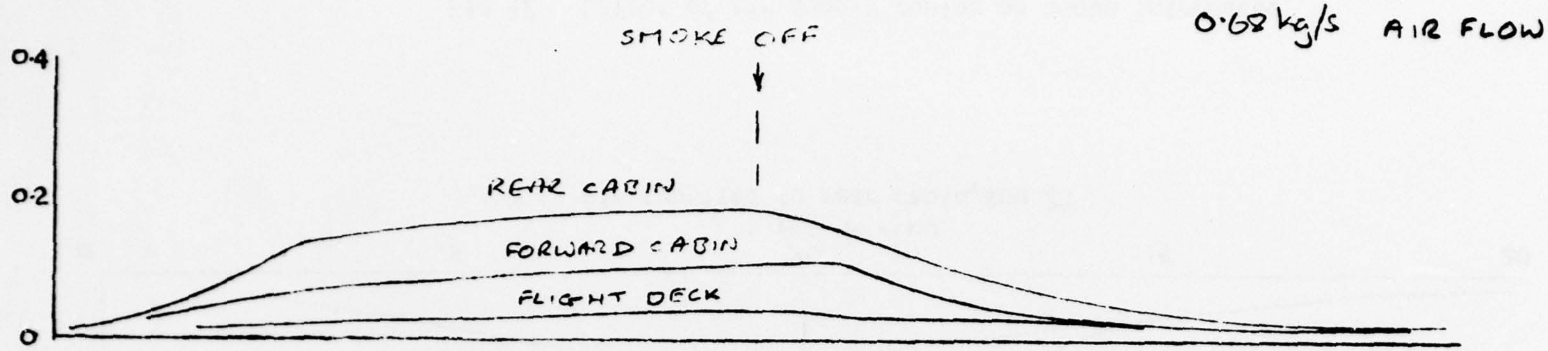
Fig 9 Effect of discharge valve settings on smoke introduced into flight deck with reduced flow rate (Phase I)



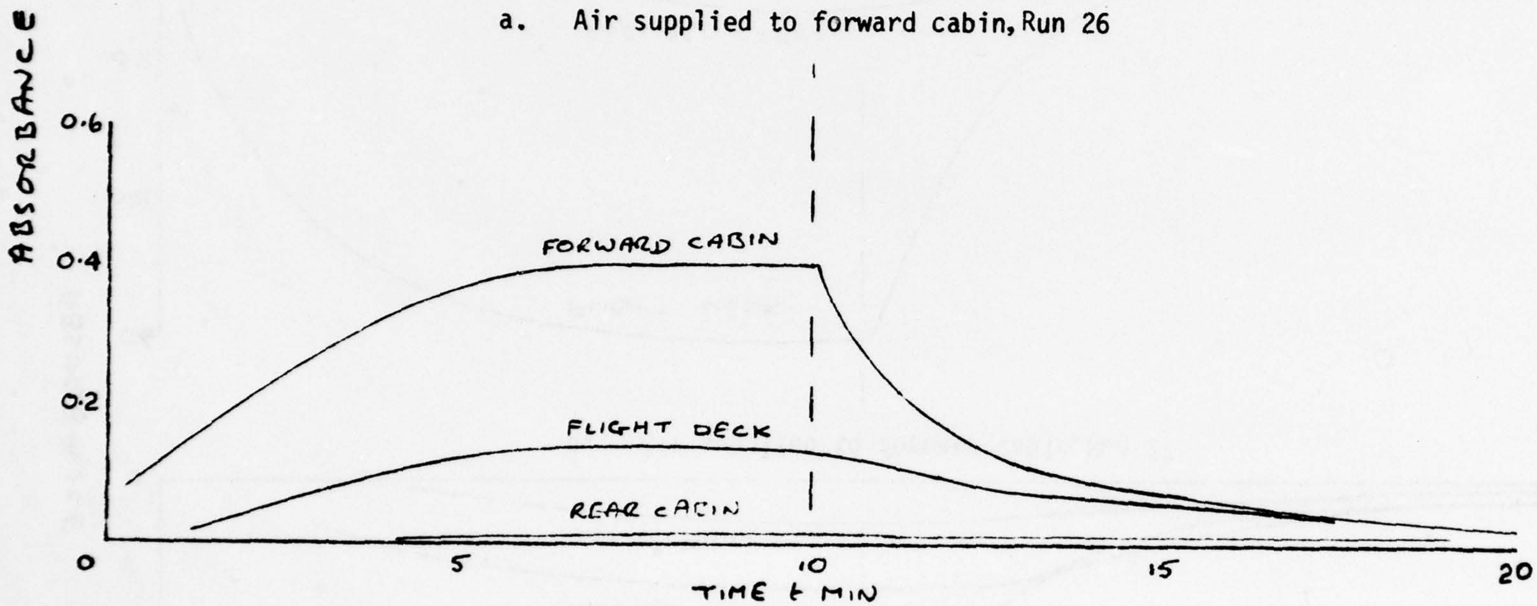

a. Air supplied to forward cabin, Run 23

b. Air supplied to rear cabin, Run 30

Fig 10 Effect of air supply zoning on smoke introduced into rear cabin (Phase II)

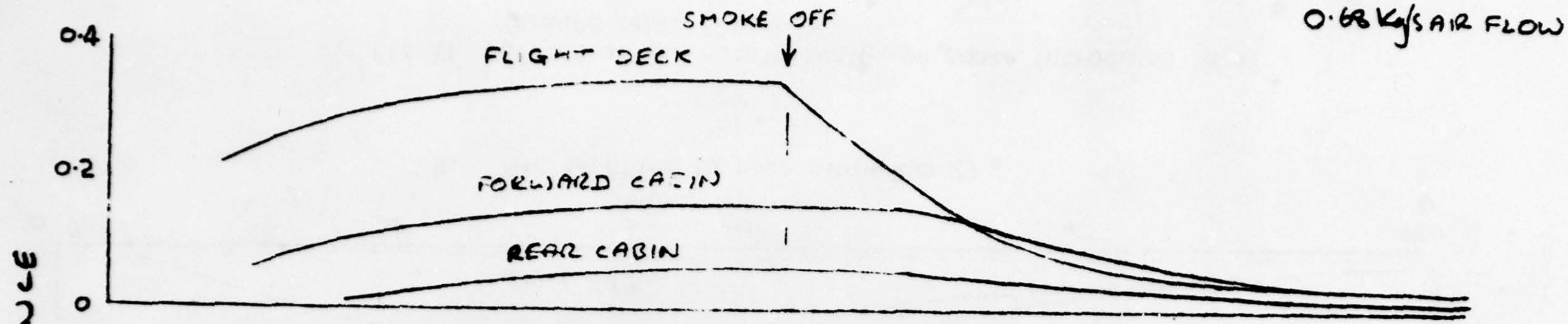



a. Air supplied to forward cabin, Run 26

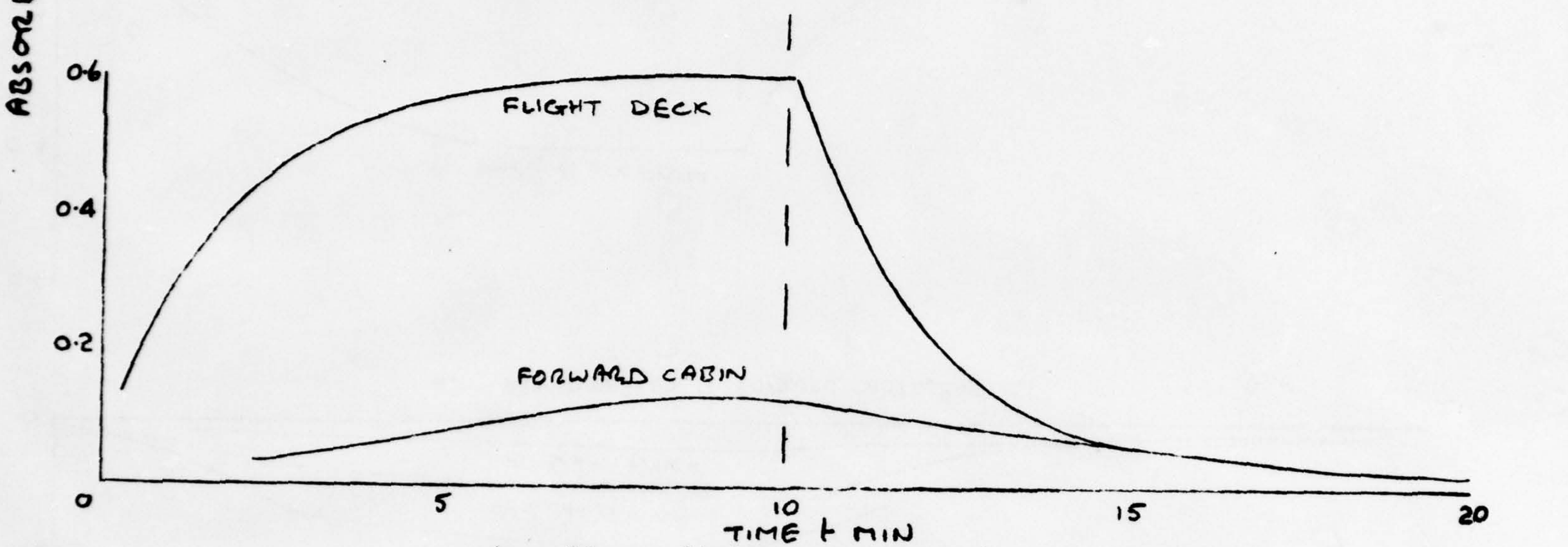



b. Air supplied to rear cabin, Run 29

Fig 11 Effect of air supply zoning on smoke introduced into forward cabin (Phase II)

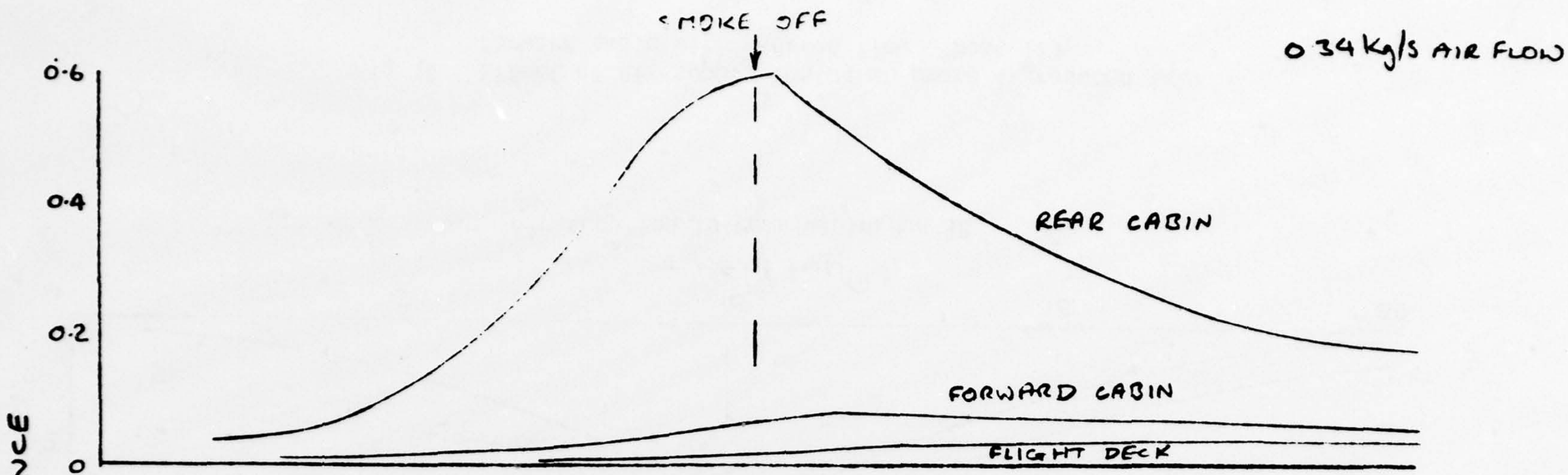



a. Air supplied to forward cabin, Run 27

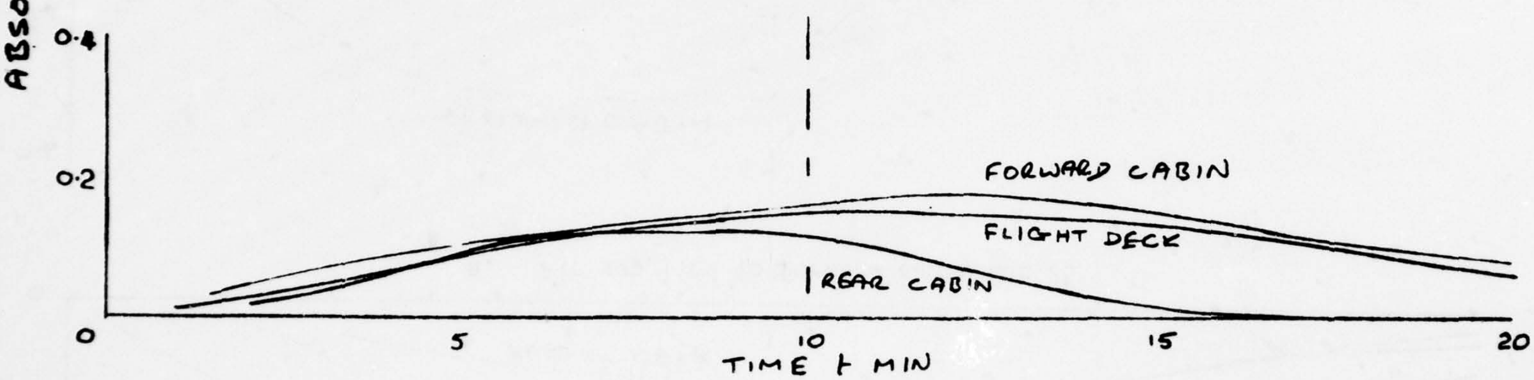



b. Air supplied to rear cabin, Run 28

Fig 12 Effect of air supply zoning on smoke introduced into flight deck (Phase II)

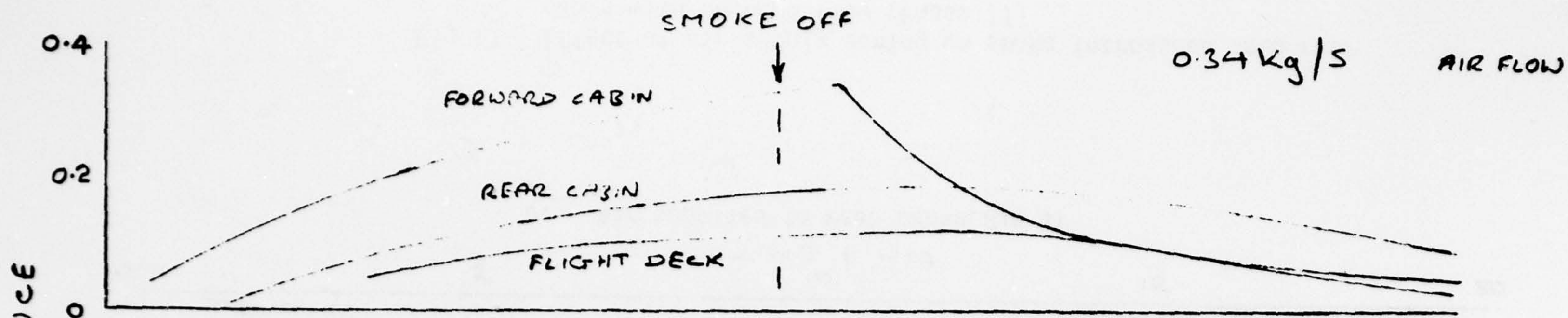



a. Air supplied to forward cabin, Run 24

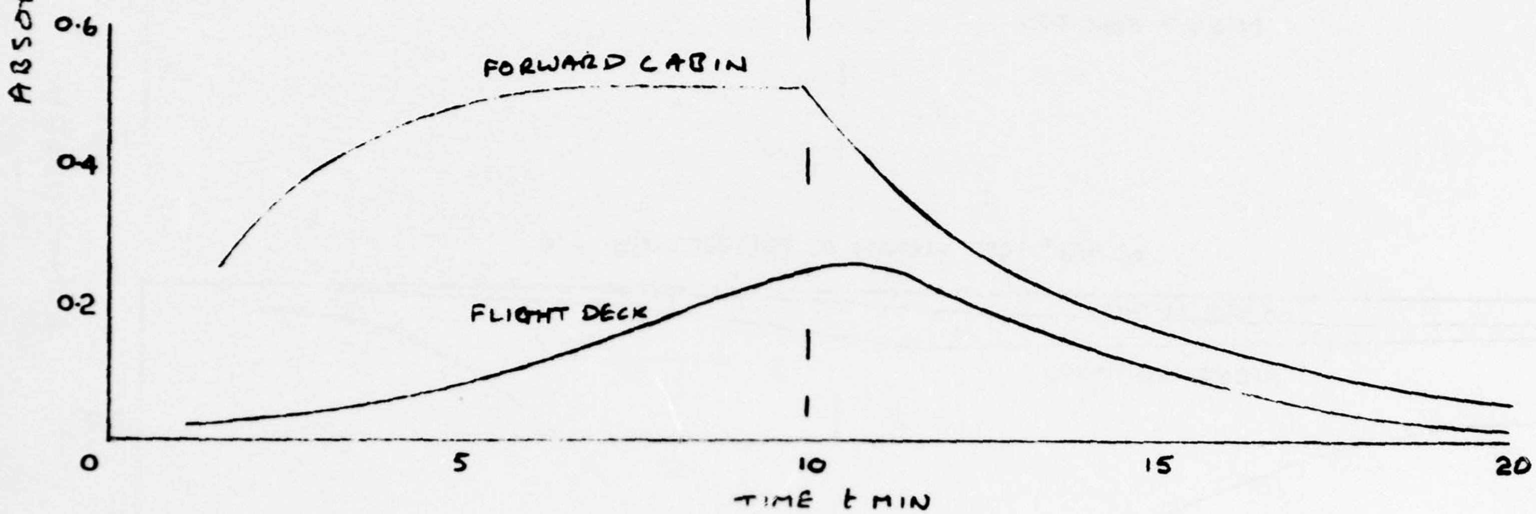



b. Air supplied to rear cabin, Run 31

Fig 13 Effect of air supply zoning on smoke introduced into rear cabin with reduced flow (Phase II)




a. Air supplied to forward cabin, Run 25




b. Air supplied to rear cabin, Run 32

Fig 14 Effect of air supply zoning on smoke introduced into forward cabin with reduced flow (Phase II)

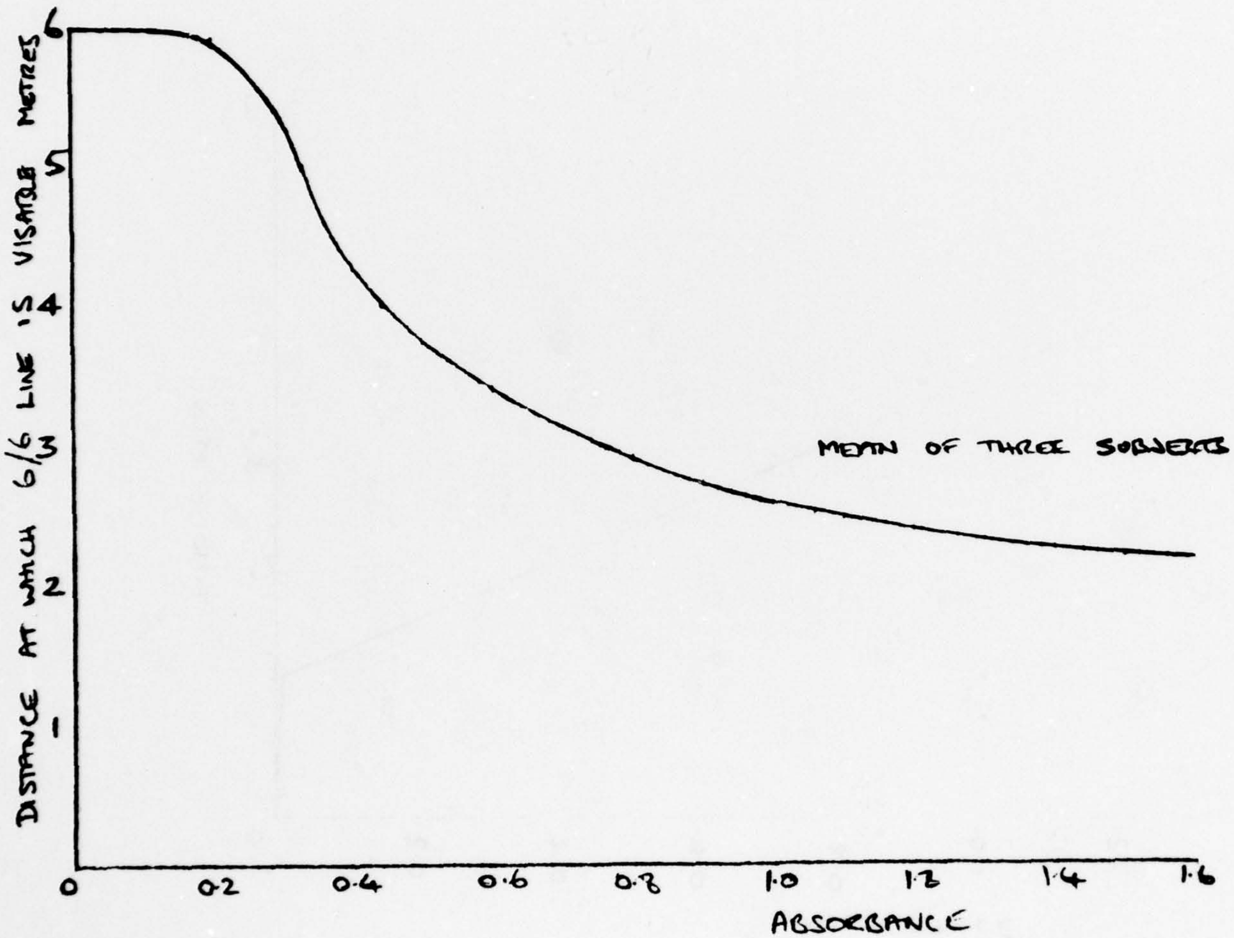



Fig 15 A correlation of visibility and absorbance (Phase III)

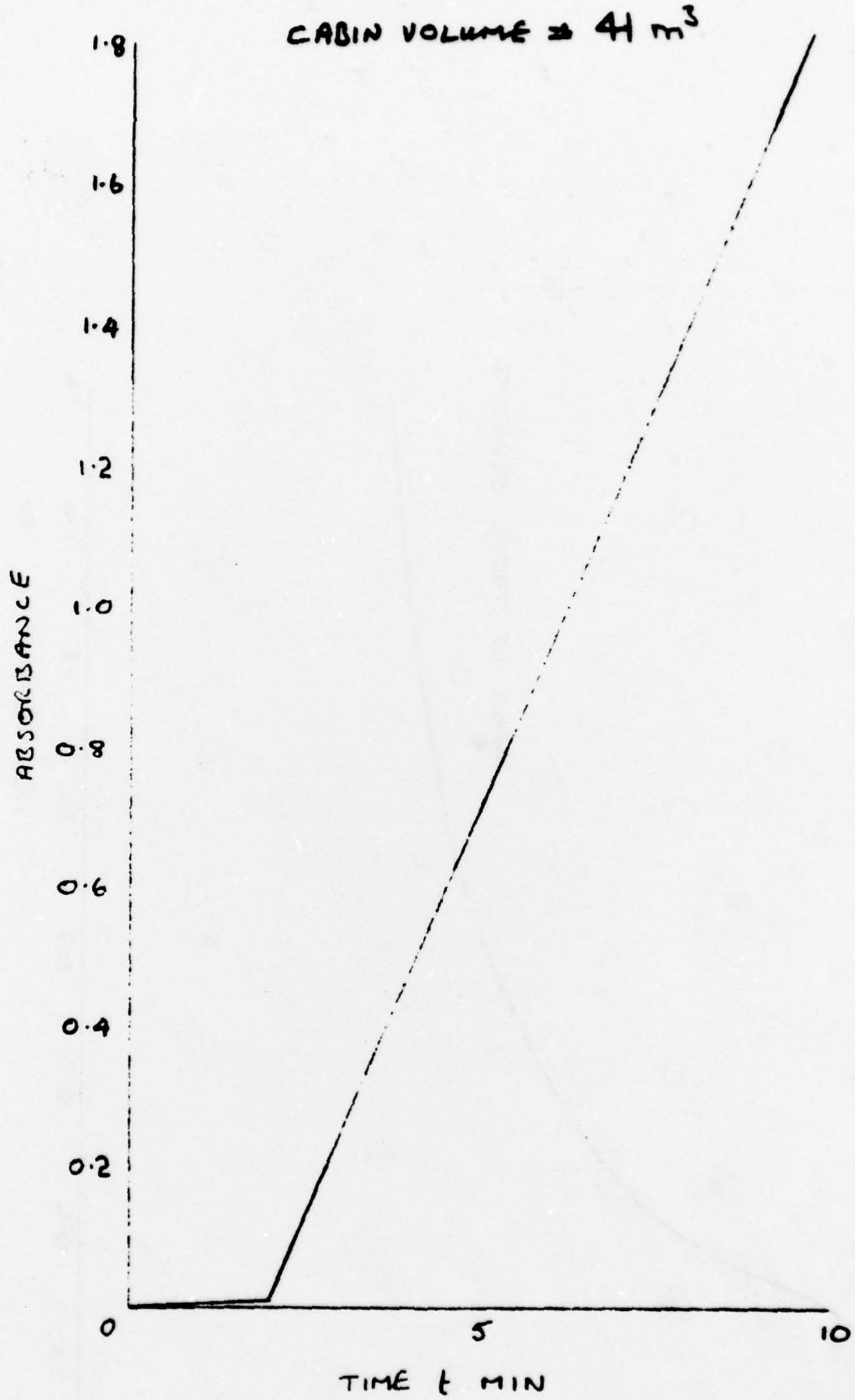



Fig 16 Effect of smoke generation in sealed forward cabin

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7b. (For Conference Papers) Title, Place and Date of Conference

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| Methven, T.J. | Webster, J.S. | | January 1978 | 28 | 3 |

| 11. Contract Number | 12. Period | 13. Project | 14. Other Reference Nos. |
|---|---|---|---|
| N/A | N/A | | |

15. Distribution statement

(a) Controlled by – ~~Head of Engineering Physics Dept, RAE~~

(b) Special limitations (if any) –

16. Descriptors (Keywords) (Descriptors marked * are selected from TEST)

Aircraft cabin smoke hazard.

17. Abstract


The migration of smoke from in-flight fires and possible measures to improve its removal have been studied in ground tests on a Comet 4B. Under normal conditions, smoke generated in various sections in the fuselage followed the air flow and dispersed throughout the fuselage before passing overboard. Biasing discharge to the front or rear affected smoke clearance only slightly but directing the total air supply to the compartment in which the smoke was generated had a beneficial effect locally, at the expense of adjacent cabins. Better clearance might be obtained in a more modern aircraft.

Tests in the flight deck showed that, in smoke laden conditions, flight instruments were best viewed with individual illumination in low ambient light. Further work with higher smoke densities is recommended.


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